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IMPROVEMENT OF THE DAMPING PROPERTIES OF CARBON-FIBRE-REINFORCED LAMINATED PLASTICS USING DAMPING LAYERS

IZBOLJŠANJE DUŠENJA Z OGLJIKOVIMI VLAKNI OJAČANE LAMINIRANE PLASTIKE Z UPORABO PLASTI ZA DUŠENJE

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A suitable hybrid composite consisting of carbon-fibre-reinforced plastic and damping layers was investigated in terms of damping and natural frequencies using experiments and numerical simulations. The frequency response and the transient response of cantilever beams were analysed. The damping layers made from rubber or from a cork-rubber composite material were used in the investigated hybrid structure. A laser-measurement device and an accelerometer were used for the measurement of the responses. Pareto optimization was performed using three-dimensional numerical simulations with the aim to maximize the fundamental natural frequency and the damping ratio.

Keywords: hybrid, composite, carbon-fibre-reinforced plastic, rubber, damping

Sestavljeni kompozit iz plastike, ojačane z ogljikovimi vlakni in s plastmi za dušenje naravnih frekvenc, je bil preiskovan eksperimentalno in z numerično simulacijo. Analiziran je bil frekvenčni odgovor in prehodni odziv konzolnega nosilca. V preiskovani hibridni strukturi je bila plast za dušenje izdelana iz gume ali sestavljena iz gume in plute. Za meritve odgovora je bil uporabljen laserski merilnik in merilnik pospeška. Z uporabo tridimenzionalne numerične simulacije je bila izvršena Paretova optimizacija za maksimiranje osnovne naravne frekvence in količnika dušenja.

Ključne besede: hibrid, kompozit, z ogljikovimi vlakni ojačana plastika, guma, dušenje

1 INTRODUCTION

Recently, the conventional metallic structures have been replaced with composite structures thanks to their superior dynamic characteristics. For example, a higher specific stiffness of carbon-fibre-reinforced plastics (CFRPs) allows higher natural frequencies of the structures. Furthermore, the damping characteristics of CFRPs have higher values and, moreover, can be improved using an integration of the damping layers[1].

The aim of this work was to develop a suitable hybrid structure in terms of damping and natural frequencies. The investigated samples were the cantilever beams, whose damping layers were made from rubber or from the ACM87 cork-rubber composite material. The damping ratio for their fundamental natural frequency was analyzed.

2 THEORY

The equation of the motion of a damped system is[2]:

$$\boldsymbol{M}\ddot{\boldsymbol{q}}+\boldsymbol{C}\dot{\boldsymbol{q}}+\boldsymbol{K}\boldsymbol{q}=\boldsymbol{f}(t) \tag{1}$$

where $\boldsymbol{q}$[m], $\dot{\boldsymbol{q}}$[m s^{-1}], $\ddot{\boldsymbol{q}}$[m s^{-2}] are the vectors of the generalized coordinates and their 1st and 2nd differentiations with respect to time t; $\boldsymbol{f}$(t)[N] is the vector of the generalized time-dependent applied force; $\boldsymbol{M}$[kg] is the mass matrix of the system; $\boldsymbol{C}$[N s m^{-1}] is the damping matrix and $\boldsymbol{K}$[N m^{-1}] is the stiffness matrix. The motion of the discrete linear systems with a single degree of freedom can be described as:

$$m\ddot{q}+c\dot{q}+kq=F(t) \tag{2}$$

In the case of free oscillations, Equation (2) can be consequently rewritten as:

$$\ddot{q}+2\zeta\omega_0\dot{q}+\omega_0^2 q=0 \tag{3}$$

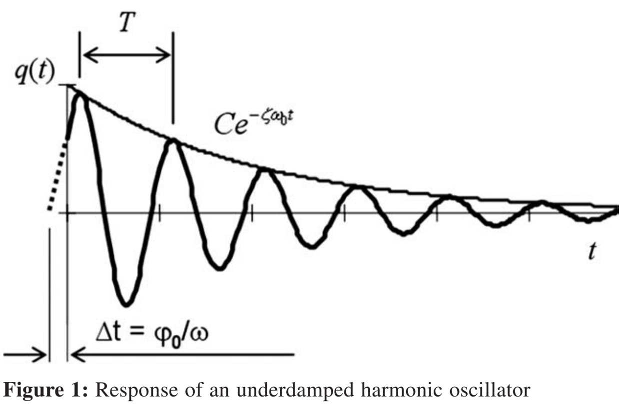

Figure 1: Response of an underdamped harmonic oscillator
Slika 1: Odgovor harmoničnega nedušenja

where the damping ratio ζ and the undamped natural frequency ω_0 are defined as:

$$\zeta = \frac{c}{2\sqrt{mk}} \tag{4}$$

$$\omega_0 = \sqrt{\frac{k}{m}} \tag{5}$$

In the case of an underdamped system ($0 < \zeta < 1$) the solution of Equation (3) representing the displacement of the system can be found in the following form:

$$q(t) = Ce^{-\zeta\omega_0 t}\sin(\omega t + \varphi_0) \tag{6}$$

where C[m] is the amplitude, ω[rad s^{-1}] is the damped natural frequency of the system and φ_0[rad] is the phase shift.

The damped natural frequency can be expressed as:

$$\omega = \omega_0\sqrt{1-\zeta^2} = \frac{2\pi}{T}2\pi f \tag{7}$$

where T[s] is the period of the waveform (**Figure 1**) and f is the damped natural frequency in Hertz.

Based on Equation (6), the exponential attenuation rate is then defined as:

$$b = \zeta\omega_0 \tag{8}$$

The damping ratio can be determined using the logarithmic decrement δ, which is defined as the natural logarithm of any two peaks:

$$\delta = \frac{1}{n}\ln\frac{q_0}{q_n} = \ln e^{-\zeta\omega_0 T} = \zeta\omega_0 T = bT = \frac{2\pi\zeta}{\sqrt{1-\zeta^2}} \tag{9}$$

where q_0 is the greater of the two amplitudes and q_n is the amplitude of a peak n periods away. The damping ratio is then found from the logarithmic decrement:

$$\zeta = \frac{\delta}{\sqrt{4\pi^2 - \delta^2}} \tag{10}$$

According to Rayleigh damping, the damping matrix $\boldsymbol{C}$ is given by:

$$\boldsymbol{C} = \alpha\boldsymbol{M} + \beta\boldsymbol{K} \tag{11}$$

where α and β are the Rayleigh constants. Assuming $\alpha = 0$ and the damping ratio ζ of both the CFRP and the damping materials is constant, the Rayleigh constant can be expressed as:

$$\beta = \frac{2\zeta}{\omega} \tag{12}$$

When the difference between the undamped natural frequency ω_0 and the damped natural frequency ω is negligible, the Rayleigh constants of the hybrid composite components can be determined as:

$$\beta_i = \frac{2\zeta_i}{\omega_{0,h}} \tag{13}$$

where ζ_i is the damping ratio of the hybrid composite component (CFRP or the damping material) and $\omega_{0,h}$ is the undamped natural frequency of the hybrid composite determined from the modal analysis.

3 EXPERIMENTS

Two types of CFRP and two types of damping layers were used in the experiments. A linear behaviour of all the materials was assumed. The mechanical properties of the materials are listed in **Tables 1** to **4**.[3] A modal analysis was used for an identification of the elastic-material properties[4].

Two cantilever flat bars consisting of unidirectional 913C-HTS CFRP and rubber were investigated. Sample A had a thickness of 7.8 mm (**Figure 2a**), sample B had a thickness of 12.9 mm (**Figure 2b**). The thickness of 913C-HTS CFRP was 2.7 mm and the thickness of rubber was 2.4 mm. The width of the bars was 19.8 mm, the length was 450 mm and the length of the clamping was 38 mm. The harmonic response after the initial deflection was investigated using an optoNCDT

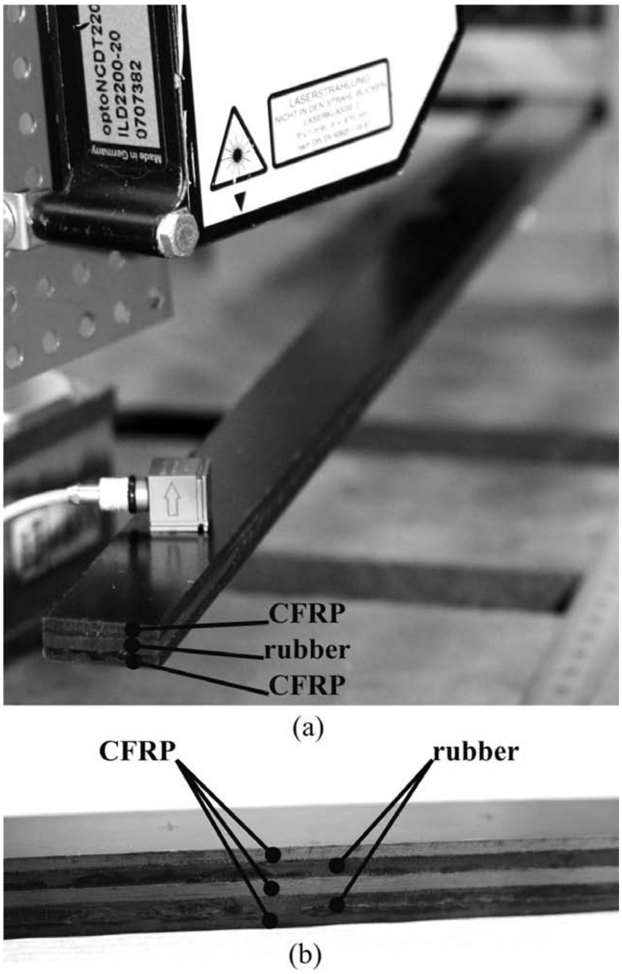

Figure 2: Cantilever flat bar consisting of 913C-HTS CFRP and rubber: a) sample A, b) sample B

Slika 2: Konzolna ploščata palica iz 913C-HTS CFRP in gume: a) vzorec A, b) vzorec B

Figure 3: Cantilever square tube consisting of K63712 CFRP and the ACM87 cork-rubber composite material: sample C
Slika 3: Konzolna kvadratna cev iz K63712 CFRP in ACM87 kompozitnega materiala pluta-guma; vzorec C

laser-measurement device or a Brüel & Kjaer 4507 accelerometer.

Table 1: Mechanical properties of 913C-HTS CFRP
Tabela 1: Mehanske lastnosti 913C-HTS CFRP

Longitudinal modulus	E_1	GPa	104
Transverse modulus	E_2	GPa	5.5
Shear modulus	G_{12}	GPa	2.4
Poisson's ratio	ν_{12}	–	0.34
Density	ρ	kg/m^3	1.500
Damping ratio	ζ	–	0.002

Table 2: Mechanical properties of K63712 CFRP
Tabela 2: Mehanske lastnosti K63712 CFRP

Longitudinal modulus	E_1	GPa	280
Transverse modulus	E_2	GPa	3.5
Shear modulus	G_{12}	GPa	1.7
Poisson's ratio	ν_{12}	–	0.38
Density	ρ	kg/m^3	1.470
Damping ratio	ζ	–	0.003

Table 3: Mechanical properties of rubber
Tabela 3: Mehanske lastnosti gume

Young's modulus	E	MPa	10
Poisson's ratio	ν	–	0.49
Density	ρ	kg/m^3	1 170
Damping ratio	ζ	–	0.072

Table 4: Mechanical properties of the ACM87 composite
Tabela 4: Mehanske lastnosti kompozita ACM87

Young's modulus	E	MPa	2.5
Poisson's ratio	ν	–	0.3
Density	ρ	kg/m^3	740
Damping ratio	ζ	–	0.112

Table 5: Results of the experiments and models
Tabela 5: Rezultati eksperimentov in modelov

	Damped natural frequency f /Hz		Damping ratio ζ	
	Exp.	Model	Exp.	Model
Sample A	35.5	37.8	0.034	0.031
Sample B	44.3	43.8	0.043	0.041
Sample C – clamped	44.0	43.7	0.039	0.004
Sample C – free	548	549	0.005	0.004

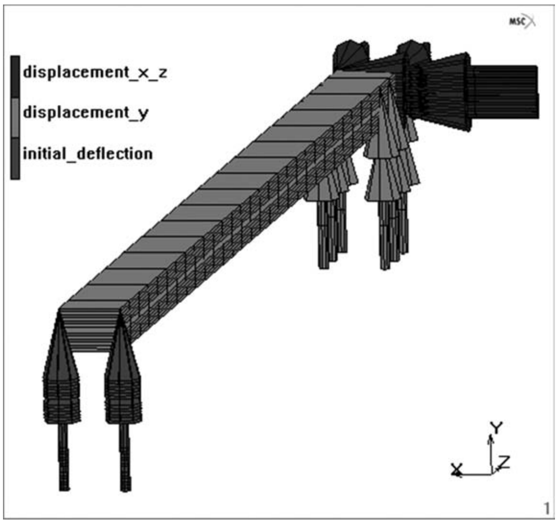

Figure 4: Boundary conditions of a model of a cantilever flat bar
Slika 4: Robni pogoji modela konzolne ploščate palice

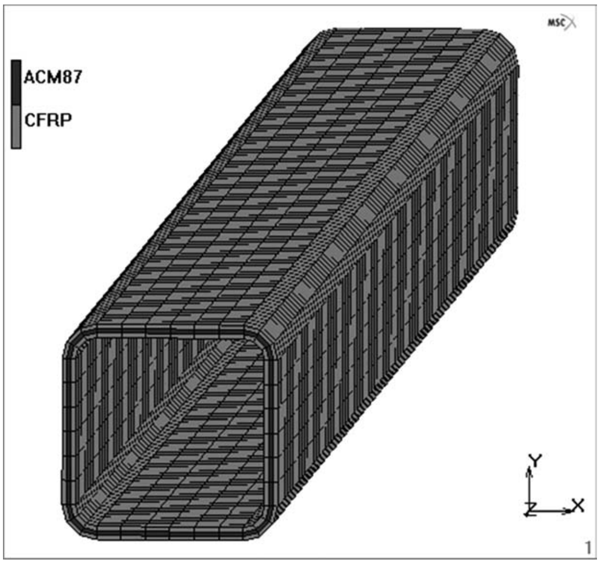

Figure 5: Model of a hybrid square tube
Slika 5: Model hibridne kvadratne cevi

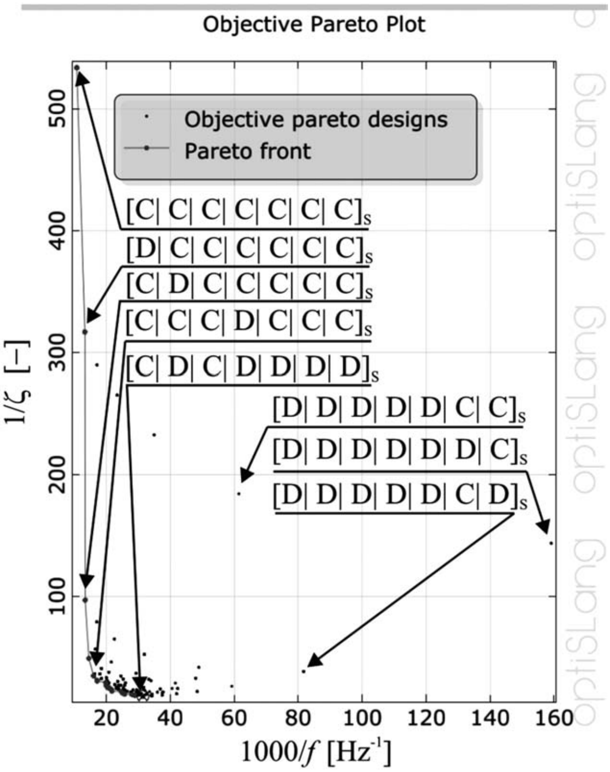

Figure 6: Pareto optimization results, "C" means CFRP, "D" means the damping layer
Slika 6: Rezultati Paretove optimizacije: "C" pomeni CFRP, "D" pomeni plast za dušenje

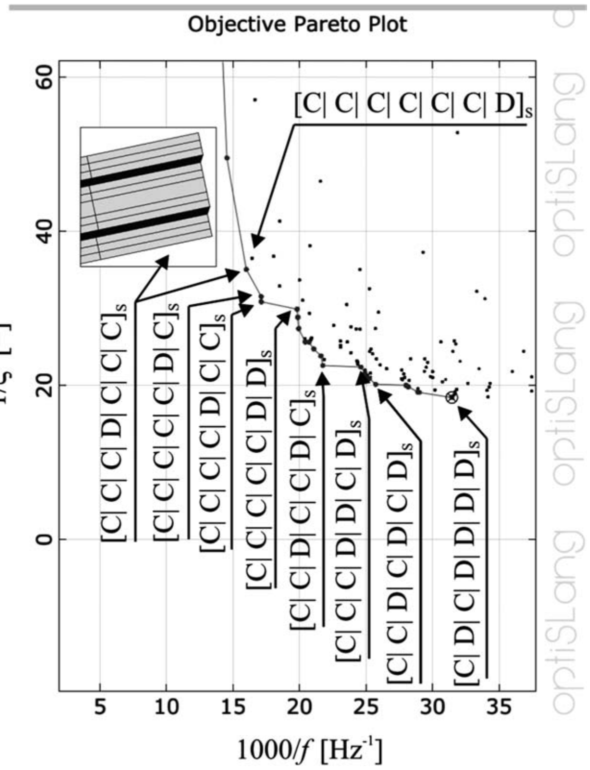

Figure 7: Detail of the Pareto front
Slika 7: Detajl Paretove linije

Further, the response of the cantilever square tube consisting of the wound K63712 CFRP and the ACM87 composite with a thickness of 6.5 mm (**Figure 3**) was investigated (Sample C). The thickness of K63712 CFRP was 2.4 resp. 2.1 mm and the thickness of the ACM87 composite was 2 mm. The width of the square tube was 103 mm, the tube length was 1 490 mm and the length of the clamping was 135 mm. However, the clamping was not sufficiently rigid. Therefore, the damping ratio was investigated also in the case of a free square tube (a tube hung on a rope).

The results are listed in **Table 5**.

4 NUMERICAL SIMULATIONS

Three-dimensional finite-element models were created in MSC.Marc using eight-node brick elements (with an assumed strain option) as shown in **Figures 4** and **5**. The CFRP materials were considered orthotropic and homogenous. The damping materials were considered isotropic and homogenous. The boundary conditions of the models of the cantilever beams are obvious from **Figure 4**. The undamped natural frequencies were obtained with a modal analysis. After an evaluation of the Rayleigh constant using Equation (12), the damped natural frequencies and the damping ratio were obtained with a transient analysis. The Newmark time integration scheme was used.

The created models were validated by comparing the experimental and numerical results listed in **Table 5**. The difference between the results for samples A and B was less than 9 %. In the case of the clamped sample C, the clamping was not sufficiently rigid as already mentioned above. Due to this fact, the damping ratio had a significantly higher value, which was confirmed with the experiment with the free sample C. The difference between the results involving the free sample C was less than 20 %.

A Pareto optimization was performed for the cantilever flat bar with the aim to maximize the fundamental natural frequency and the damping ratio. The analyzed bar was a symmetrical hybrid laminate with 14 layers consisting of 913C-HTS CFRP and rubber. The thickness of the layers was 1 mm and the fibre orientation of the CFRP layers was identical to the beam axis. The width of the bar was 20 mm, the length 450 mm and the length of the clamping was 30 mm. The Pareto front is shown in **Figure 6**, a detail of the front in **Figure 7**. It is obvious from both figures that the situation is very complex; therefore, the problem should be more precisely constrained.

5 CONCLUSION

The performed experiments and numerical simulations showed that the investigated natural frequencies and damping ratios of the hybrid composite structures strongly depend on the placement of the damping layers in the hybrid cross-sections. The accurate place of the damping layers must be investigated for each application in dependence on the material of the layers, the geometry and the requested ratio between the fundamental natural frequency and the damping ratio.

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